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DESIGN CONSIDERATIONS FOR VEHICULAR FUEL CELL POWER PLANTS*

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ABSTRACT

Fuel cells show great promise as an efficient, nonpolluting vehicular power source that can operate on nonpetroleum fuel. As with other power sources, design tradeoffs can be made that either improve vehicle performance or reduce the size and cost of the fuel cell power system. To evaluate some of these tradeoffs, a number of phosphoric acid fuel cell power plant designs have been studied to determine the performance level they would provide, both for a compact passenger vehicle and a 40-ft city bus. The fuel is steam reformed methanol.

The analyses indicate that 1978 fuel cell technology can provide a 22 to 50% improvement in fuel economy over the 1980 EPA estimate for the conventionally powered General Motors X car. With this technology the city bus can meet the DOT acceleration, gradability, and top speed requirements. A reasonable advance in fuel cell technology improves performance and fuel consumption of both vehicles substantially.

I. INTRODUCTION

Fuel cells are a promising alternate power source for vehicular applications.[1-10] They are efficient, nonpolluting, can operate on nonpetroleum fuel, and could provide a vehicle with good performance, long-range, and low-energy consumption. As with other power sources, design tradeoffs can be made that either improve vehicle performance or reduce the size and cost of the fuel cell power system. To evaluate some of these tradeoffs, a number of fuel cell power plant designs have been studied to determine the performance level they would provide for a compact passenger vehicle. In addition, a 40-ft city bus with a fuel cell power plant has been evaluated. The power plant considered in this paper is the phosphoric

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acid fuel cell (PAFC) system operating on methanol, which is steam reformed on board the vehicle. The fuel cell used for the consumer vehicle is based on data supplied by Energy Research Corporation (ERC) for a 1978 study of fuel cells for transportation.[2] In addition, two advanced fuel cells are considered for consumer vehicles. The first has a polarization curve increased by 75 mV over the base line; the second is improved by 150 mV. The city bus uses a fuel cell based on the 500-h characteristics of the United Technologies Corporation (UTC) 40-kW on-site fuel cell power plant.

Design tradeoffs can be made on the fuel cell power system to improve vehicle performance or reduce the size and cost of the fuel cell. Each of the fuel cell systems was analyzed at two operating points. Operation at a low-power density provides high efficiency and a high peak/nominal power ratio. The benefits are reduced fuel consumption and improved vehicle performance. On the other hand, operating the fuel cell at a high-power density reduces fuel cell weight, volume, catalyst requirement, and cost. Vehicles with six different fuel cell power plants are analyzed and the cost/performance tradeoffs are examined.

The vehicles were analyzed with a fuel cell/battery vehicle simulation program developed at Los Alamos National Laboratory. A detailed analysis of component operation and interaction, in terms of voltage, current, fuel consumption, torque, and angular velocity as a function of time, is used to calculate the vehicle's performance and fuel consumption for each drive cycle specified.

II. CONSUMER VEHICLE

The consumer vehicle is based on the body and chassis of the General Motors X car that has a rolling friction of 0.0114 lb/lb and an aerodynamic drag factor of 0.417. The drive train retained the 4-speed manual transmission, but the final drive ratio was changed to meet design requirements. The base-line vehicles use current technology fuel cell data and the following currently available electrical components:

- A dc, series-wound, 20-hp Prestolite motor.
- An SCR chopper controller with bypass and field weakening.
- A 4.8-kWh (20-h rate) lead-acid battery.

Except for the battery, these components are also used for the advanced fuel cell vehicles. An advanced battery based on nickel-zinc battery data is used with the advanced fuel cells. This reduces the battery weight by 176 lb. The primary purpose of the battery is to provide vehicle power during fuel cell warm-up, although it does provide some peaking power.

The base-line fuel cell data were supplied by ERC in 1978[2] and are consistent with the characteristics of a 2-kW stack recently obtained from ERC. The nominal operating point for this fuel cell is 0.6V/cell and 150 A/ft^2 (ASF). The two advanced fuel cells have characteristics improved by 75 mV and 150 mV. These three fuel cell systems were each analyzed at two operating points. The first is at a low-power density for maximum performance; the second is at a high-power density for minimum fuel cell cost, weight, and volume. This led to the following six power sources that were analyzed for the General Motors X car.

- Base-line fuel cell (0.6 V/cell, 150 ASF)
- Base-line fuel cell operation at higher power density for light weight/minimum fuel cell (0.5 V/cell, 436 ASF)
- Base line +75 mV designed for fuel economy (0.675 V/cell, 150 ASF)
- Base line +75 mV designed for light weight/minimum fuel cell (0.6 V/cell, 356 ASF)
- Base line +150 mV designed for fuel economy (0.75 V/cell, 150 ASF)
- Base line +150 mV designed for lightweight/minimum fuel cell (0.6 V/cell, 580 ASF)

Some characteristics of the base-line fuel cell stack are listed in Table I.

Each vehicle was designed to cruise at 60 mph with the controller in bypass and had a top speed (with field weakening) of 65 to 70 mph. The batteries were sized for a 15-min fuel cell start-up time. That is, the vehicle can be driven for 15 min on the batteries until the fuel cell reaches its operating temperature.

The results of the analyses are summarized in Table II. In each case the gasoline equivalent fuel consumption was substantially less than the EPA estimate for the conventionally powered General Motors X car. The improvement in the combined urban and highway driving ranged from 53% for the base-line fuel cell to 100% for the +150 mV advanced fuel cell. Note also that for the fuel-cell-powered vehicle the mileage on the urban driving schedule (UDS) is nearly the same as for the highway driving schedule (HDS) while for the internal-combustion-engine- (ICE) powered vehicle the UDS mileage is substantially lower. This is because the fuel cell efficiency increases slightly at reduced power levels. The efficiency of an ICE is reduced substantially when the power level is throttled back.

The 0- to 50-mph acceleration time of the base-line vehicle was designed to be comparable to that of today's diesel-powered passenger cars. The advanced fuel cells provide a substantial improvement in 0- to 50-mph time. The weight of the base-line vehicle is increased by 724 lb, while the weight of the advanced fuel cell vehicle is less than 100 lb over that of the ICE vehicle.

III. CITY BUS

The city bus has some significant advantages for an early vehicular application of fuel cells. These advantages include centralized refueling, centralized maintenance, better control of maintenance and operating conditions, offsetting higher initial cost with possible lower maintenance costs, a larger volume to work with, and less problem with increased weight.

The performance of a 40-ft, 48-passenger (full seated load), 102-in.-wide city bus is evaluated. The bus is based on the General Motors of Canada, Ltd., Model T8H53074.[14] A 134-hp, series-wound, dc motor is used. The motor characteristics are scaled from the General Electric BT2376 (36 hp at 120 V, 2100 rpm). The controller is an SCR chopper with bypass and field weakening. Batteries were not used for the bus since start-up time should not be a problem and the fuel cell met the peak power requirements. The fuel cell is based on the 500 h characteristics of the UTC 40 KW on-site power plant. The nominal operating point is 0.643 V/cell at 160 ASF. In addition, the system was analyzed at a high power density operating point (0.5 V/cell, 446 ASF). Tables III and IV list some of the bus and fuel cell stack characteristics.

The bus was designed to have a cruise capability of 58 mph to easily meet the 55 mph cruise requirement of the Department of Transportation

(DOT) commuter driving schedule. The top speed is about 65 mph, which exceeds the DOT requirement of 60 mph.

The analysis results for the city bus are summarized in Tables V and VI. The maximum performance bus meets all of the DOT acceleration and gradability requirements and is just under the maximum curb weight.[13] The methanol mileage on the DOT composite design operating profile ranges from 2.11 with the hotel load to 2.64 mpg without the hotel load (4.59- to 5.74-mpg diesel equivalent).

The bus with the minimum cost power plant meets the low-power alternative requirements and all but the 2.5% gradability requirement for the standard bus. However, the lower efficiency fuel cell operating point results in a 24% reduction in the composite cycle mileage.

IV. CONCLUSIONS

The analyses indicate that fuel cells show great promise for both the consumer vehicle and the city bus. The 1978 base-line fuel cell technology can provide a 22 to 50% improvement in fuel economy for the ICE-powered X car. An improvement of 75 mV can provide a 70% improvement even when the fuel cell size, weight, and cost are minimized. The longer term 150-mV improvement can provide up to 100% improvement in fuel consumption. The city bus, with current technology, can meet the DOT acceleration, gradability, and top speed requirements, and gets 2.11 mpg of methanol (4.59-mpg diesel equivalent) on the DOT composite operating profile for buses.

The design tradeoffs available allow substantial flexibility in matching a fuel cell power source to a particular application. For the consumer vehicle, operation at a high-power density would reduce the front-end cost and the weight and volume of the power source. These benefits are obtained at the cost of increased fuel consumption and reduced performance, although the calculated fuel consumption is still substantially lower than that of the ICE vehicle.

On the other hand, a fuel cell power plant operating at a lower power density seems more appropriate for the city bus. The higher front-end cost may well be offset by the lower fuel costs over the life of the bus. Further, the additional weight and volume required by the lower power density source are less important for the bus.

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TABLE I

BASE-LINE FUEL CELL STACK AND REFORMER FOR THE CONSUMER VEHICLE*

	Maximum Performance	Minimum Cost
Operating point (V/cell)	0.6	0.5
Current density (ASF)	150	438
Power density (W/ft^2)	90	219
Number of cells	160	192
Cell area (ft^2)	1.39	0.476
Total area (ft^2)	222	91.4
Rated power (kW)	20	20
Projected peak power (kW)	66	27
Nominal voltage	96	96
Average efficiency (UDS)	39.9	35.7
Weight (lb)	680	364

*Based on 1978 ERC design.[2]

TABLE II

SUMMARY OF COMPACT PASSENGER VEHICLE SIMULATION RESULTS

	General Motors X Car 4-Cylinder, 4-Speed Manual Transmission	Base Line Maximum Performance	Base Line Minimum Cost	Base Line +75 mV Maximum Performance[3]	Base Line +75 mV Minimum Cost[3]	Base Line +150 mV Maximum Performance[3]	Base Line +150 mV Minimum Cost[3]
Total weight (lb)[1]	2895	3619	3440	3143	3025	3121	2981
Fuel cell weight	--	680	364	380	262	358	218
Mileage[2]							
UDS	24.0	46.5	35.6	53.4	48.5	57.7	49.2
HDS	38.0	46.2	38.6	60.4	55.9	64.6	58.2
Combined	30.3	46.4	37.0	56.5	51.9	60.8	53.3
0-50 mph time (seconds)	--	15.5	17.7	12.7	14.1	12.4	15.3
Top speed	--	67.6	66.7	67.5	66.4	67.4	65.5
Average fuel cell/overall efficiency (UDS)	--	39.9/26.5	35.7/19.6	44.1/27.2	41.5/24.1	48.4/30.6	43.9/24.3

[1]Curb weight plus 300 lb for passengers
[2]Gasoline equivalent
[3]Advanced battery technology is used with the advanced fuel cells. This reduces battery weight by 176 lb.

TABLE III

FUEL-CELL-POWERED 40-FT CITY BUS

Bus - engine	22,350-2,850 = 19,500
Fuel cell and reformer	4,420
DC motor and controller	980
Air conditioning	1,300
Wheel chair lift	600
Curb weight	26,800
Forty-eight passengers (full seated load)	7,200
Simulation weight	34,000
Rolling friction	0.01 lb/lb
Frontal area	74 ft^2
Drag coefficient	0.707
Hotel load	15 kW
Controller current limit	400 A

TABLE IV

FUEL CELL STACK AND REFORMER FOR CITY BUS*

	Maximum Performance	Minimum Cost
Operating point (V/cell)	0.643	0.500
Current density (ASF)	160	446
Power density (W/ft^2)	103	223
Number of cells	576	740
Cell area (ft^2)	2.2	0.79
Total area (ft^2)	1,267	583
Rated power (kW)	130	130
Projected peak power (kW)	331	152
Nominal voltage	370	370
Average efficiency (CBD)	42.5	34.5
Weight (lb)	4,420	2,600

*Based on UTC 40-kW, 500-h data.[11]

TABLE V

CALCULATED BUS PERFORMANCE

	DOT Requirement (6/80)		Simulation Result	
	Standard	Low Power Alternative	Maximum Performance	Minimum Cost
Top speed (mph)	60	50	65	61
Max. acceleration times (s)				
0-10 mph	5.6	6.0	2.9	2.9
0-20 mph	10.1	12.0	7.6	8.0
0-30 mph	19.0	24.0	15.8	17.2
0-40 mph	34.0	45.0	28.6	32.5
0-50 mph	60.0	--	48.9	59.9
Gradability (mph)				
2.5%	44	34	49	39
12.0%	--	7	13	12
16.0%	7	--	9	8
Max. curb weight (lb)	27,2[illegible]0		26,800	24,950

TABLE VI

CALCULATED CITY BUS FUEL CONSUMPTION, MILES PER GALLON OF METHANOL*

	Maximum Performance		Minimum Cost	
	With 15-kW Hotel Load	Without Hotel Load	With 15-kW Hotel Load	Without Hotel Load
Central business district (20 mph)	2.05	2.63	1.58	2.27
Arterial (40 mph)	2.16	2.47	1.56	1.93
Commuter (55 mph)	3.22	3.64	2.37	3.02
Composite	2.11	2.64	1.61	2.25
Steady 55 mph	3.75	4.34	3.05	3.68

*Multiply by 2.17 to get diesel equivalent.